Renewable and Sustainable Energy Reviews 41 (2015) 1167–1175

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Mercury emissions by Beijing's fossil energy consumption: Based on environmentally extended input–output analysis

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ARTICLE INFO

Article history:
Received 18 June 2014
Received in revised form
11 August 2014
Accepted 26 August 2014

Keywords:
Embodied mercury emissions
Fossil energy
Beijing
Input–output analysis

ABSTRACT

Fossil energy burning is one of the most important sources of atmospheric mercury emissions, which poses great threats to both environment and human health. Urban regions are dominant energy consumers; however, the information on the resultant mercury emissions in urban regions has been lacking. Therefore, in light of environmentally extended input–output analysis, this study used Beijing as a case to investigate embodied (direct plus indirect) mercury emissions induced by fossil energy consumption in urban regions. The results show that embodied mercury emissions caused by Beijing's fossil energy consumption amounted to 5.86 tonnes, which is over 1.5 times the direct emissions, indicating that the conventional direct emission accounting method will lead to significant emission leakage. Coal combustion takes the major responsibility for energy-related mercury emissions. As a net importer of embodied mercury emissions, Beijing avoided a considerable amount of mercury emissions. Sectors like construction which play key role in embodied mercury emissions are also identified in this study. To comprehensively reduce mercury emissions from energy consumption the Beijing government should devote efforts to develop clean coal technology and high efficiency mercury removal devices, shift investment from infrastructure construction to tertiary industries and optimize green consumption among the residents, especially the urban residents. The method and findings may be useful for compilation of overall urban mercury emissions inventory as well as have important policy implications for global cities to control mercury emissions.

Contents

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http://dx.doi.org/10.1016/j.rser.2014.08.073
1364-0321/

1. Introduction

Mercury, with wide distribution and long range transport, is a highly toxic pollutant which can pose adverse effects on both human and wildlife health. On these features, mercury is widely regarded as one of the most important air pollutants in the world [1,2]. Given the air pollutant's global significance, some researchers have accounted the global mercury emissions. Pacyna and Pacyna estimated that the global emission of mercury from anthropogenic sources was 1900 tonnes in 1995 [3], and stationary fossil energy combustion was emphasized as one of the main sources. Then a series of studies compiled the global mercury emissions in the following years [4–8]. Without exception fuel energy consumption, especially coal combustion, stands for the largest single contributor to mercury emissions into air in the existing global inventories.

Due to energy's large contribution to global mercury emissions, numerous studies were also carried out to analyze the fossil energy-related mercury emissions in different countries. For instance, Dabrowski et al. estimated that the average amount of atmospheric mercury emissions from coal burned power plants in South Africa is 9.8 tonnes per year [9]. Mercury emission from coal-fired power plants in Poland contributed to about 40% of the total emissions, which amounted to 20.1 tonnes in 2005 [10]. The existing national inventories also include those of India, the United States, Canada, etc. [11,12]. As the largest developing country in the world, China emerges as the top energy consumer as well as the largest atmospheric mercury emission emitter. Global Mercury Assessment 2013 issued by United Nation Environmental Protection Agency reports that China is responsible for about one-third of the global atmospheric mercury emissions, making China the largest individual contributor [13]. Energy activities, especially coal combustion, are considered to be the most important anthropogenic mercury emissions sources in China [14]. According to previous studies, just coal combustion in China caused about 40% of mercury emissions to ambient air environment in the country [8,15].

Urban regions are regarded as the main energy consumers across the world, which consumed about two-third of the world's energy in recent years [16]. This situation is more evident in China, where urban regions are responsible for over three quarters of the country's total commercial energy use [17]. Moreover, under the ongoing trend of urbanization in China, an additional 350 million people will be projected to live in urban regions in China over the next 15 years [18]. It can be predicted that a greater amount of fossil energy will be consumed by the urban regions and inevitably, the massive energy burning will have huge impact on our atmospheric environment by releasing air pollutants like gaseous mercury. Therefore urban regions, as the most important energy consumers, can be regarded as the main contributors for energy-related atmospheric mercury emissions in China. Without doubt, establishing a valid estimate of atmospheric mercury emissions from energy consumption in urban regions is vital for air pollution control in China.

However, given the significance of urban energy consumption, no specialized efforts have been made to investigate atmospheric mercury emissions from specific urban regions' energy consumption, as the existing studies concentrate on larger scale emission studies or specific emission sites. Moreover, it should be noted that most of the previous studies paid attention to the mercury emissions from only coal combustion; comprehensive research on more energy types is still lacking.

Additionally, previous studies on mercury emissions were mainly conducted from the traditional production perspective, i.e., just focusing on atmospheric mercury directly emitted by the human activities such as coal burning, industrial production and waste incineration. The direct accounting method pays attention only to the direct emissions from the end users, ignoring the complex transaction between different sectors. As a matter of fact, the urban economy is a network which connects all the economic sectors that are interdependent in this network. Except for the end use of energy, each sector also induces indirect energy consumption which refers to energy embodied in intermediate inputs. Consequently, besides the end-of-pipe mercury emissions, economic sectors also lead to indirect emissions because of the indirect energy consumption. For instance sector construction requires products such as cement, electricity, steel, etc., whose production processes are supported by direct energy inputs. As a result, the consumption of construction sector leads to indirect mercury emissions from other sectors. Given this, to draw a holistic picture of urban mercury emissions, the embodied mercury emissions by urban economy, which is defined as the sum of direct (on-site) and indirect (supply-chain) emissions, should be investigated.

Beijing, the capital city of China, has been suffering severe air pollution for years. The frequent bursts of air pollution have not only posed great threat on people's health but also caused considerable economic loss [19]. Although there have already been numerous studies on other air pollutants (e.g. [20]) mercury emissions, an air pollutant with global importance caused by the city, is still an open field. Therefore, Beijing was selected as a case in this study to draw a holistic picture of an urban economy's energy-related atmospheric mercury emissions. The main objectives of the present study are (1) to estimate the local mercury emissions from energy combustion based on the latest data in light of a comprehensive accounting method; (2) to compare the sectoral distribution of embodied mercury emissions from energy source; (3) to carry out the embodiment analysis for energy-related mercury emissions by final consumption from the consumption perspective; and (4) last but not the least, to support appropriate air pollution abatement policy formulation by providing scientific evidences.

The rest of the paper is structured as follows: Section 2 shows an overview of embodied emission related studies, Section 3 articulates the methodology employed in this study, Section 4 summarizes the detailed results, the direct and indirect results are compared and relevant policy implications are discussed in Section 5, and in the final section conclusions are drawn.

2. An overview of embodied emission related studies

The main focus of this research is to account the embodied mercury emissions caused by various economic activities' energy consumptions in Beijing. Embodied mercury emission is an indicator which sums all the emissions induced by the production of products and services in the supply chain. The concept can be useful in comparing the technological level of both sectors in the same economy and a targeted sector in different economies.

Basically, there are two widely accepted methodologies for embodied emission analysis: life cycle assessment (LCA) and input–output analysis (IOA).

LCA is a technique to assess the potential environmental impacts associated with a commodity during all of its life cycle, i.e., from cradle to grave. The framework of LCA approach includes four main steps, namely goal and scope, life cycle inventory, life cycle impact assessment and interpretation of results. As it enables the decision makers to avoid a narrow outlook on environmental issues, a large number of studies have adopted LCA to inventory environmental emissions in recent years. For instance, Murphy et al. analyzed the greenhouse gas emissions in forest biomass supply chains in Ireland [21]. Menten et al. compared the greenhouse gas emissions results for advanced biofuels by reviewing LCA studies and identified the factors which have impacts on emission estimate [22]. Branco et al. showed that the advantage of carbon capture toward climate change mitigation was mainly reduced when the LCA was performed [23]. These LCA-based literatures have contributed significantly to supporting policy makers to inform decisions by providing the detailed information for revealing the embodied energy effects assignable to products. Besides, LCA studies were also carried out to investigate embodied elements in the field of renewable energy [24–26], water footprint [27–29], etc. Although LCA method is a powerful tool for evaluating the embodied emissions, there are arguments on LCA's shortcomings, e.g., a lack of consistency in tracking emissions during the life cycle of objects concerned as inevitable truncation exists at several stages, very time-consuming and the infinite trace process [30]. Therefore, LCA is usually used to evaluate the embodied effects of specific commodities [31,32].

IOA, first proposed by Leontief [33,34], is an alternative evaluation method for analyzing the embodiment effects. Based on the sectoral monetary transaction data in economic input–output table, IOA is capable of providing a panorama of embodied ecological element flows as it shows the complex interdependencies of the economic network. In contrast to LCA, IOA is more suitable for evaluating the macro-scale economies which cover all the commodity flows on a consistent basis [35]. As a result IOA, a methodology for benchmarking embodiment analysis, has been widely accepted and applied to evaluate different ecological emissions [36–42], and other ecological elements such as energy (e.g. [31,32,39,43]), water (e.g. [35,44–46]), etc. Additionally, a certain number of previous studies have specifically employed IOA to investigate embodied ecological emissions for urban regions (e.g., [30,47–50]). It should be noted that IOA based research on mercury emissions is still an open field, except for a few studies on China's national mercury emissions [51,52]. However, no such efforts based on environmentally extended have been devoted to perform embodiment analysis for the atmospheric mercury emissions caused by the dominant energy consumers – urban regions. To fill the gap, our study made an attempt to account for the overall mercury emissions from energy consumption in a specific urban region.

3. Method and data sources

3.1. Direct atmospheric mercury emissions

The current study only takes the atmospheric mercury emissions caused by main fossil energy burning. The direct mercury emissions calculation is based on the amounts of fossil energy consumed and their corresponding emission factors. The data sources will be elaborated in the following sections.

3.2. Input–output analysis

With reference to [50,53], the input–output table for Beijing economy was constructed to combine economic activities with resources use and environmental emissions. The basic row balance of Beijing input–output table can be described as

$$X + X^{im} = AX + F \tag{1}$$

where X is the total output, X^{im} of imports, A denotes technology coefficients matrix whose element $a_{i,j}$ represents the direct input from Sector i to Sector j, AX stands for the intermediate inputs, and F denotes the final demand. By introducing the identity matrix I, the form of Eq. (1) can be transformed as

$$F - X^{im} = X - AX = (I - A)X \tag{2}$$

Due to the lack of emission intensity data on imported commodities (both domestic and abroad) it is assumed that the sectoral embodied emission intensities of imports are the same as those of local sectors, according to existing studies [37,54]. Based on this assumption, the mercury emissions balance can be demonstrated as

$$AM + \varepsilon AX = \varepsilon X \tag{3}$$

where AM is the row of total amount of direct mercury emissions caused by sectoral energy consumption, and ε is the embodied mercury emission intensity. Therefore, with Eqs. (2) and (3), the embodied mercury emission intensity ε can be derived as

$$\varepsilon = am(I - A)^{-1} \tag{4}$$

where am is the vector of direct intensity of sectoral atmospheric mercury emissions obtained by AM_i/X_i, indicating that Sector i's total direct emission is divided by its total output, I is the identity matrix, and $(I - A)^{-1}$ is the Leontief inverse matrix [55].

Mercury emissions embodied in trade balance (EEB) are also considered in this current study. Mercury emissions embodied in imports (EEI), which reflect the amount of mercury emission avoided by Beijing via imports, can be obtained as

$$EEI = \varepsilon X^{im} \tag{5}$$

Likewise, mercury emissions embodied in exports (EEE) can be expressed as

$$EEE = \varepsilon X^{ex} \tag{6}$$

where X^{ex} is the vector of exports. Therefore, EEB can be calculated as

$$\text{EEB} = EEE - EEI \tag{7}$$

3.3. Data sources

The economic input–output table for Beijing economy is provided by Beijing Statistical Bureau [56]. It is the latest table which covers 42 economic sectors (seen in Table 1). Data on direct fossil energy data are collected from Beijing Statistical Yearbook 2011. Furthermore, the emission factors of each energy type are derived from [57].

4. Results

4.1. Direct emissions

The direct mercury emissions from fossil energy combustion in Beijing are calculated as 3.78 tonnes in 2010. Fig. 1 shows the structure of different emission sources. Among all the energy types coal burning is the prominent emitter, contributing about 85% of

Table 1
Sectors for the economic input–output table for Beijing 2010.

Code	Sector
1	Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy (Agriculture)
2	Coal Mining and Dressing
3	Petroleum and Natural Gas Extraction
4	Ferrous and Nonferrous Metals Mining and Dressing
5	Nonmetal and Other Minerals Mining and Dressing
6	Food Processing, Food Production, Beverage Production, Tobacco Processing
7	Textile Industry
8	Garments and Other Fiber Products, Leather, Furs, Down and Related Products
9	Timber Processing, Bamboo, Cane, Palm and Straw Products, Furniture Manufacturing
10	Papermaking and Paper Products, Printing and Record Medium Reproduction, Cultural, Educational and Sports Articles
11	Petroleum Processing and Coking, Gas Production and Supply
12	Raw Chemical Materials and Chemical Products, Medical and Pharmaceutical Products, Chemical Fiber, Rubber Products, Plastic Products (Chemical Products Related Industry)
13	Nonmetal Mineral Products
14	Smelting and Pressing of Ferrous and Nonferrous Metals
15	Metal Products
16	Ordinary Machinery, Equipment for Special Purpose
17	Transportation Equipment
18	Electric Equipment and Machinery
19	Electronic and Telecommunications Equipment
20	Instruments, Meters Cultural and Office Machinery
21	Manufacture of Artwork and Other Manufactures
22	Waste
23	Electric Power/Steam and Hot Water Production and Supply
24	Gas Production and Supply Industry
25	Water Production and Supply Industry
26	Construction Industry
27	Transport and Storage
28	Post
29	Information Transmission, Computer services and Software
30	Wholesale, Retail Trade
31	Hotels, Catering Service
32	Financial Industry
33	Real Estate
34	Leasing and Commercial Services
35	Research and Experimental Development
36	Polytechnic Services
37	Water conservancy, Environment and Public Facilities Management
38	Service to Households and Other Service
39	Education
40	Health, Social Security and Social Welfare
41	Culture, Sports and Entertainment
42	Public Management and Social Organization

the total direct emissions. Following this is kerosene and gasoline combustion, with a proportion of 6.43% and 5.82%, respectively. Petroleum gas and fuel oil play much less important role, both accounting for less than 1% of the total.

For each sector, the direct mercury emissions from each economic sector vary significantly (Fig. 2). Sector 23 (*Electric Power/Steam and Hot Water Production and Supply*) emits 1.89 tonnes atmospheric mercury by fossil energy combustion, accounting for half of the total direct emissions. The reason can be explained by Sector 23's dominant role in coal consumption; in 2010, 46.66% of the coal consumed by Beijing is attributed to this sector. The second largest and third largest sectoral emitters are Sector 27 (*Transport and Storage*) and Sector 4 (*Ferrous and Nonferrous Metals Mining and Dressing*), respectively. Together with Sector 23, they contribute two-thirds of the total.

The direct emission intensity is also depicted in Fig. 3. However, the trend of emission intensity is not completely consistent with the sectoral emissions. Sector 23 also releases 8.73 kg mercury into air from fossil energy combustion per unit of output. The second and third largest emission intensities belong to Sector 4 (*Ferrous and Nonferrous Metals Mining and Dressing*) and Sector 5 (*Nonmetal and Other Minerals Mining and Dressing*). It should be noted that for some tertiary sectors, even though the amount of emissions is small, their emission intensities rank very high. Take Sector 28 (*Post*) as an example: its amount of direct emissions is 17th among all the sectors, while it has the 4th highest direct emission intensity.

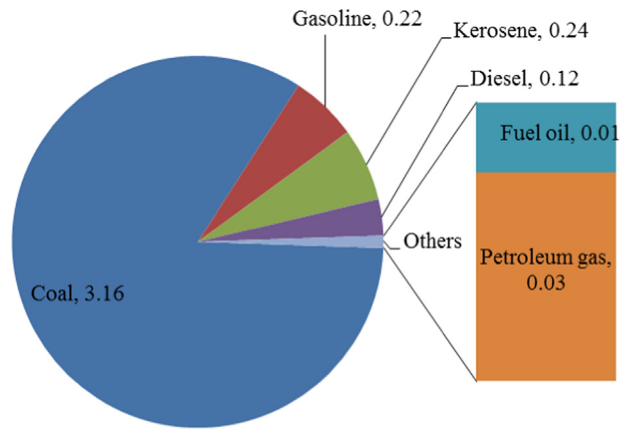


Fig. 1. The structure of fuel energy sources for direct mercury emissions.

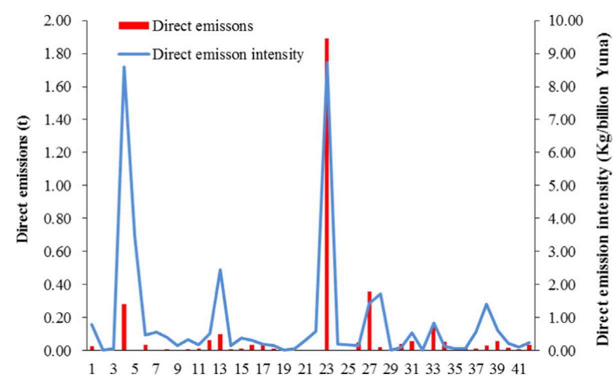


Fig. 2. Sectoral direct emissions and intensities.

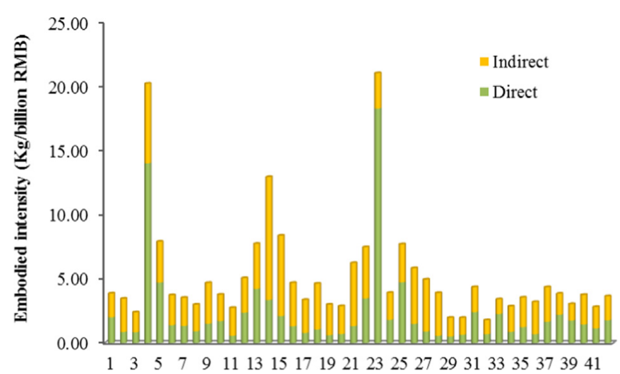


Fig. 3. Embodied mercury emission intensity for each sector.

4.2. Embodied emissions

Presented in Fig. 3 is the embodied mercury emission intensity for each sector of Beijing economy in the year of 2010. Sector 23 (*Electric Power/Steam and Hot Water Production and Supply*) has the largest embodied mercury emissions caused by fossil energy

combustion produced per unit output, with a volume of 21.05 kg/billion RMB. This can be explained by the fact that Sector 23 is the main supplier of electricity and heating power for other sectors. The second emission-intensive sector is Sector 4 (*Ferrous and Nonferrous Metals Mining and Dressing*), whose embodied emission intensity is 21.02 kg/billion RMB, followed by Sector 14's (*Smelting and Pressing of Ferrous and Nonferrous Metals*) 12.96 kg/billion RMB. Notably, except for a few sectors like Sectors 23 and 4, most of the sectors' embodied mercury emission intensities are dominated by indirect emission intensities. Based on sectoral embodied intensities, the average sectoral embodied mercury emission intensity induced by Beijing's fossil energy consumption is calculated as 4.50 kg/billion RMB, which is more than two times the value of average sectoral direct mercury emission intensity (2.05 kg/billion RMB).

Presented in Fig. 4 is the contribution from both coal and oil products to Beijing's sectoral embodied mercury emissions. Except for Sector 27 (*Transportation*) and 28 (*Post*), coal dominated the sectoral energy-related mercury emissions. This is due to two main reasons: (1) the mercury emission factor of coal is much higher than that of oil products [57]; (2) coal has the largest fraction in Beijing's energy structure [56]. Generally, embodied emissions caused by coal burning contributed to over 85% of the average embodied mercury intensities.

4.3. Emission embodied in trade

Table A1 shows the distribution of energy related mercury emissions embodied in exports (*EEE*) and imports (*EEI*). Mercury emissions embodied in exports amount to 7.47 tonnes, of which 23.82% is due to foreign exports while 66.18% is due to domestic exports. The largest sectoral exporter is Sector 4 (*Ferrous and Nonferrous Metals Mining and Dressing*) with an amount of 0.85 tonnes, followed by Sector 26 (*Construction*) with the quantity of 0.69 tonnes and Sector 36 (*Polytechnic Services*) with an amount of 0.57 tonnes. Meanwhile, Beijing avoids 9.55 tonnes energy related mercury emissions by importing materials and products from other regions both home and abroad (also shown in Table A1). Similar to exports, domestic imports dominated the total imported mercury emissions (66.77%) and foreign imports accounted for slightly less than one-fourth. The ranking of importing sectors contrasts with that of exporting sectors in the order of amount of mercury emissions. The largest energy related mercury emissions importing sector is Sector 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*) with a value of 1.59 tonnes, followed by Sector 4 (*Ferrous and Nonferrous Metals Mining and Dressing*) with an amount of 0.77 tonnes and Sector 27 (*Transport*) with a quantity of 0.71 tonnes. Moreover, the structures of emissions embodied in exports and imports vary from each other. For imports, the primary, secondary and tertiary industry contributed 1.90%, 79.51% and 18.59%, respectively, to the total mercury emissions embodied in exports. Unlike the exports, even though the secondary still takes the prominent proportion (64.74%) of the total imported mercury emissions, the tertiary industry takes much larger percentage (34.96%) compared with that of imports.

Based on *EEI* and *EEE*, the net energy related mercury emissions embodied in trade balance (*EEB*) are obtained and the distribution on sectoral basis is depicted in Fig. 5. The sectors with positive embodied emissions are considered net mercury emissions exporters while those with negative embodied emissions are net mercury emissions importers. For the net exporters, Sector 36 (*Polytechnic Services*) is the largest individual sectoral exporter with an amount of 0.57 tonnes, followed by Sector 32's (*Financial Industry*) 0.30 tonnes, Sector 29's (*Information Transmission, Computer services and Software*) 0.26 tonnes and Sector 34's (*Leasing and Commercial Services*) 0.25 tonnes. For the net importers Sector 14 (*Smelting and Pressing of Ferrous and Nonferrous Metals*), with 1.12 tonnes net imported emissions, ranked the first among all the net importers. Sectors 27 and 23 are, respectively the second and third largest net importers. It is obvious that most of the net exporters concentrate in tertiary industries whereas most of the net importers are secondary industry sectors. This fact indicates the characteristics of Beijing economy, i.e., on one hand, it heavily depends on imports of industrial products and resources and on the other hand its tertiary industry sectors supply services to other regions.

4.4. Emissions embodied in final consumption

The total energy related mercury emissions embodied in Beijing's local final consumption were calculated as 5.86 tonnes in the year of 2010. The final consumption is constituted by five different categories: rural household consumption, urban household consumption, government consumption, capital formation and inventory increasing. Capital formation contributed the largest proportion of the total final consumption, with a percentage of 43.45%, followed by urban household consumption's 29.05%, government consumption's 19.44%, inventory increase's 5.62% and rural household consumption's 2.44%. The prominent contribution of capital formation is due to the intensive investment in Beijing, which is equivalent to 43.20% of the total GDP in 2010 [56]. Notably, the contribution of urban household consumption is more than ten times that of rural household consumption while their direct emissions were comparable. The reason behind this pattern is that the energy embodied in urban embodied consumption is much higher than that embodied in rural household consumption, due to larger population as well as the more energy-intensive lifestyle. Therefore, the energy-related mercury emissions induced

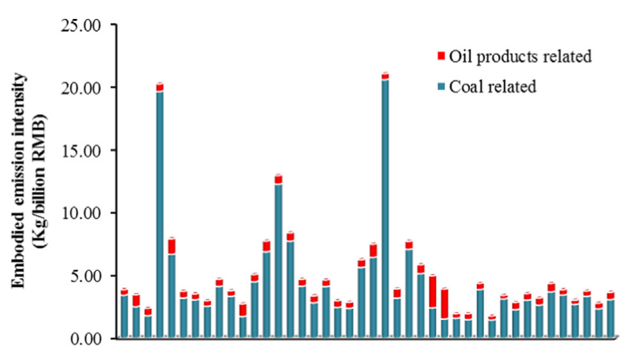


Fig. 4. The component of coal- and oil products related embodied mercury emission intensities.

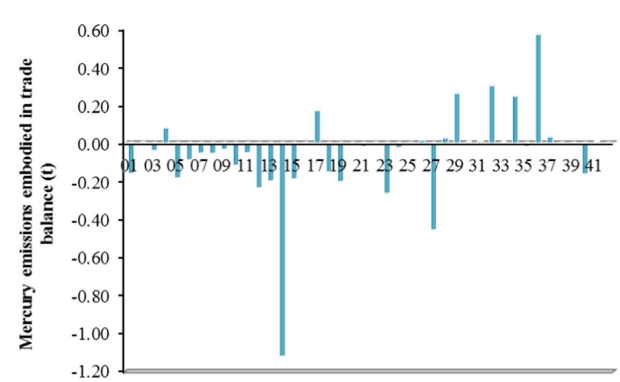


Fig. 5. Energy related mercury emissions embodied in trade balance.

by urban household consumption are much higher than those caused by the rural household consumption.

Fig. 6 presents the distribution of energy related mercury emissions embodied in Beijing's final consumption. Sector 26 (*Construction*) holds the top position as the largest embodied atmospheric mercury emitter, contributing over a quarter to the total emissions embodied in final consumption. The ongoing infrastructure construction along with the urbanization has strong impact on energy related mercury emissions, as construction activities require massive energy intensive products and materials such as electricity, steel and cement. Prominently Sector 26's large emissions can be basically attributed to capital formation, accounting for more than 95% of the total. Similarly, Sector 33 (*Real Estate*), 17 (*Transportation Equipment*) and 29's (*Information Transmission, Computer services and Software*) large amounts of embodied mercury emissions are also dominated by emissions embodied in capital formation. Obviously, Sector 35 (*Research and Experimental Development*), 39 (*Education*), 40 (*Health, Social Security and Social Welfare*) and 42 (*Public Management and Social Organization*) contributed to relatively large quantity of emission embodied in final consumption as well. Government consumption is responsible for embodied mercury emissions in those sectors, as shown in Fig. 6.

5. Discussion

Beijing provides a typical example of urban consumption, which is heavily reliant on products and resources provided by other regions. Thus, its consumption has impacts such as resources depletion (energy and water exploitation) and environmental emissions (greenhouse gas emissions and other air pollutants) in other places (e.g. [30,58]). The results in this study show that embodied atmospheric mercury emissions from fossil energy combustion of Beijing show the same characteristics as those of other embodied ecological elements consumption/emissions caused by this urban economy, i.e., the amount of embodied mercury emissions far exceeds that of direct emissions. The traditional way of analyzing mercury emission, which takes direct effect into consideration only, will cause significant emission leakage problems. Moreover this study assumes that the embodied mercury emission intensities of imports are the same as those of the local production sectors, which would lead to underestimation of embodied mercury emissions from energy use in Beijing. This is because the domestic imports which dominated the total imports must have much higher mercury emission intensities than that of the coal-dominated energy structure in China.

In recent years, Beijing has been suffering heavy air pollution, which has brought great threats on its environment and residents' health. Therefore, the mitigation of air pollutants such as mercury is in urgent need. To tackle the mercury emissions, Beijing can take actions from both the production and consumption perspective.

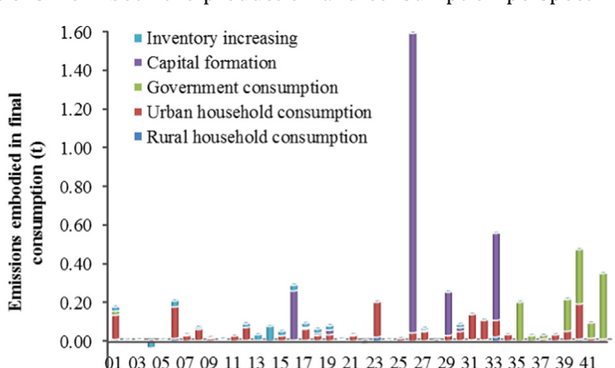


Fig. 6. Emissions embodied in final consumption.

From the results we found that coal combustion was responsible for over 85% of the total fossil energy related mercury emissions caused by the Beijing economy in 2010. Therefore, controlling the atmospheric mercury emissions from coal combustion is vital for Beijing's clean air efforts. There are some measures that can be taken to reduce coal burning induced mercury emissions. First, the government can increase efforts to develop clean coal technology to reduce the mercury emissions from their sources. Additionally, electrostatic precipitator devices and cyclones have been testified as effective mercury removal devices [57]. Moreover some low-cost functional sorbents which can be used in removal devices have been developed [59,60], which can further enhance those devices' efficiency. Therefore, the second crucial measure is that mandatory regulations should be issued by the government: all the sectors with coal boilers should install mercury removal devices with efficient sorbents. However, according to Wu et al. [15], although the installation rate of mercury removal devices has reached over 95% in coal-fired power plants since 1980s, the installation rate in industrial sectors lags far behind. Given this, there is much work to be done to increase the installation in all of the coal used sectors. Third, adjustment of energy structure in Beijing is also important for energy-related mercury emissions. Compared to coal, natural gas can be considered as a cleaner energy source with much less air pollutant emissions [13]. Regarding this, Beijing government has increased the fraction of natural gas in energy mix to ease its over-reliance on coal in recent years. Last but not the least, increasing the energy efficiency would be very helpful for not only mercury emission reduction but also other air pollutants abatement. These mercury emissions suggestions are in agreement with the clean air five year plan unveiled in 2013, aiming to reduce the impact of energy combustion on environment and human health [61].

Besides the aforementioned measures implemented from the production perspective, actions should be taken also from the consumption perspective. Liang et al. demonstrated that capital formation and population growth are the main divers of atmospheric mercury emissions [51]. According to the results obtained in the study, capital formation induced the largest amount of energy related mercury emissions in Beijing especially in the construction sector. This is due to the intensive investment that has flowed into large-scale infrastructure construction in Beijing [56], as it is one of the most important economic engines for economy. It is well known that the infrastructure construction is strongly tied to energy-intensive industrial sectors as the construction processes consume massive iron and steel, concrete, cement and electricity produced by these sectors [37]. Moreover, running machines in these sectors requires a great deal of energy consumption, during which the atmospheric mercury will be released. Consequently, to rationally control the development of construction sector and shift investment to tertiary sectors such as research and design, technological innovation will be beneficial for not only long-term economic growth but also mercury emission abatement in Beijing.

Under the circumstance of China's urbanization, the urban population is booming at an unprecedented growth rate. The flow of people from rural communities as well as other regions into Beijing raises many problems, among which massive fossil energy use and the related air pollution are the acute ones. From the calculated results we found that the embodied mercury emissions caused by urban household energy consumption are more than 10 times that induced by rural household energy consumption. It can be easily predicted that urban energy consumption and the resulting mercury emissions will keep growing along with the ongoing urbanization. Therefore, avoiding disorderly urban population growth is also an effective measure to control the mercury emissions in Beijing. Furthermore, the consumption behaviors of

expanding middle-class and affluent people in developing countries have strong influence on environmental problems [62]. It is impractical to curb the environmental pollution if we ignore urban residents consumption behaviors. As a result, the government should take the initiative to optimize urban residents green consumption such as using energy saving products and saving electricity to reduce mercury emissions and other energy related pollution.

Uncertainty exists in results of embodied mercury emissions as the intensity data were assumed to be the same as Beijing's local emission intensities data. As a matter of fact, it is impossible that both the foreign and domestic imports have the same embodied emission intensities due to the various energy mix and technology levels. As Beijing's energy consumption heavily relies on trade, it can be implied that external trade has significant influence on Beijing's embodied mercury emissions. Therefore, further research is clearly needed to differentiate the mercury emissions caused by local production, domestic and foreign trade.

6. Conclusions

China's unprecedented urbanization and rapid economic growth have led to gargantuan energy consumption in recent decades. Subsequently, the enormous urban energy combustion that resulted in air pollutants emissions threatens both ecosystem and human health. Among all the air pollutants mercury, as a high toxic pollutant, has attracted global concerns. However, the information on atmospheric mercury emissions caused by urban energy consumption has been lacking. Therefore, this article used Beijing as a case to quantify the atmospheric mercury emissions resulting from fossil energy consumption. For the purpose of drawing a holistic picture of atmospheric mercury emissions induced by Beijing's energy consumption, a prevailing systematic method named IOA has been employed to investigate energy related embodied mercury emissions caused by Beijing economy in the year of 2010.

The atmospheric mercury emissions directly emitted by end use of fossil energy in Beijing amounted to 3.78 tonnes, with an overwhelming percentage of over 80% contributed by coal combustion. Compared to coal, oil products were responsible for a much smaller fraction. On the sector basis, Sector 23 (*Electric Power/Steam and Hot Water Production and Supply*) holds the top position as the largest individual sectoral emitter. Analysis in this study indicates that the traditional approach of calculating the urban mercury emissions, which takes only on-site emissions into consideration, will lead to emission leakage. Based on IOA, the embodied mercury emissions caused by Beijing's final energy consumption reached 5.86 tonnes. Mercury emissions induced by capital formation's final energy consumption contribute the largest share of the total emissions embodied in final consumption, followed by urban household consumption, government consumption, inventory increase and rural household consumption. The mercury emissions embodied in imports exceeds that embodied in exports, making Beijing a net importer of energy related mercury emissions, which also implies that Beijing avoids 2.08 tonnes mercury emissions via trade.

As Beijing has been suffering heavy air pollution, policy implications for overall mercury emissions abatement are also discussed in this study. Efforts can be made from both production and consumption perspectives. As coal is responsible for the majority of Beijing's both direct and embodied mercury emissions caused by energy consumption, it is vital to control mercury emissions from coal burning. Therefore, the government is advised to strive to develop clean coal and mercury removal technologies and install high efficiency mercury removal devices into coal boilers. Moreover, improving energy efficiency is also an important way to reduce Beijing's mercury abatement. On the basis of consumption perspective, as the embodied mercury emissions are much larger than direct emissions, the city's mitigation efforts should break the limits of direct emission focused framework. However, for comprehensive emission abatement, measures should be implemented to reduce the embodied mercury emissions. As capital formation is responsible for significant proportion of the total embodied mercury emissions driven by the investment in large scale construction, to shift investment to tertiary industry would be beneficial for controlling energy related embodied mercury emissions. Additionally, to promote green consumption among local residents is also an effective way to help both energy conservation and mercury emissions reduction.

In summary this case study is not only an initial effort to trace the embodied mercury emissions for Beijing, but also provides insights for comprehensive accounting for global urban regions. For a long time the accounting for urban emissions was confined in the framework of "Scope 1" (direct emissions from urban geographical boundary) and "Scope 2" (direct emissions plus indirect emissions from several outside sources like electricity) [63,64], which will likely lead to emission leakage. If the urban regions' emission reduction actions are guided by direct emission information, the mitigation efforts may bring about perverse incentives and a "local emission reduction at the cost of overall rise" situation [65–67]. To solve the emission problems, our study established an IOA based accounting for overall mercury emission caused by energy consumption in an urban region. We hope that the present study will contribute to research on inventorying embodied mercury emission as well as other air pollutants induced by other global cities, especially those heavily relying on trade. Moreover, the specific mercury emission reduction measures such as energy structure adjustment also have transferability to robust policy making in urban regions which have similar socioeconomic and energy structures as those of Beijing.

Acknowledgment

This research was supported by the National Natural Science Foundation of China (Grant no. 11272012).

Appendix A

See Appendix Table A1.

Table A1
The mercury emissions embodied in trade (in tonnes).

Sector Code	Foreign import	Domestic import	Total import	Foreign export	Domestic export	Total export	Trade balance
01	0.08	0.10	0.18	0.02	0.00	0.02	−0.16
02	0.00	0.04	0.04	0.02	0.02	0.04	0.00
03	0.47	0.04	0.51	0.00	0.46	0.47	−0.04
04	0.73	0.04	0.77	0.01	0.84	0.85	0.08
05	0.00	0.19	0.19	0.01	0.00	0.01	−0.18
06	0.04	0.23	0.27	0.01	0.17	0.18	−0.09
07	0.01	0.08	0.08	0.01	0.02	0.03	−0.05
08	0.00	0.09	0.09	0.02	0.02	0.04	−0.05
09	0.00	0.05	0.05	0.00	0.01	0.01	−0.03
10	0.01	0.12	0.13	0.00	0.01	0.01	−0.12
11	0.04	0.20	0.24	0.09	0.10	0.19	−0.05
12	0.09	0.52	0.61	0.05	0.33	0.38	−0.23
13	0.00	0.30	0.30	0.01	0.10	0.10	−0.20
14	0.10	1.49	1.59	0.18	0.29	0.47	−1.12
15	0.00	0.19	0.19	0.01	0.00	0.01	−0.19
16	0.06	0.09	0.15	0.02	0.12	0.14	−0.01

Table A1 (*continued*)

Sector Code	Foreign import	Domestic import	Total import	Foreign export	Domestic export	Total export	Trade balance
17	0.18	0.19	0.37	0.06	0.48	0.54	0.17
18	0.04	0.23	0.27	0.02	0.09	0.12	−0.15
19	0.08	0.51	0.59	0.17	0.22	0.39	−0.20
20	0.02	0.00	0.03	0.00	0.02	0.02	−0.01
21	0.01	0.16	0.16	0.01	0.13	0.15	−0.02
22	0.00	0.02	0.02	0.00	0.02	0.02	0.00
23	0.00	0.27	0.27	0.00	0.00	0.00	−0.26
24	0.00	0.02	0.02	0.00	0.00	0.00	−0.02
25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	0.11	0.56	0.67	0.23	0.45	0.69	0.02
27	0.62	0.09	0.71	0.20	0.05	0.25	−0.46
28	0.00	0.00	0.00	0.00	0.03	0.03	0.03
29	0.03	0.02	0.04	0.05	0.26	0.31	0.26
30	0.06	0.21	0.26	0.05	0.22	0.27	0.00
31	0.02	0.11	0.13	0.00	0.13	0.14	0.01
32	0.01	0.00	0.01	0.01	0.31	0.32	0.30
33	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34	0.20	0.00	0.21	0.45	0.00	0.45	0.25
35	0.04	0.00	0.04	0.01	0.02	0.03	−0.02
36	0.00	0.00	0.00	0.00	0.57	0.57	0.57
37	0.00	0.02	0.02	0.00	0.05	0.05	0.04
38	0.00	0.00	0.00	0.00	0.00	0.00	0.00
39	0.10	0.00	0.10	0.01	0.09	0.10	0.00
40	0.00	0.18	0.18	0.00	0.01	0.01	−0.16
41	0.01	0.05	0.06	0.00	0.06	0.06	0.01
42	0.02	0.00	0.02	0.02	0.00	0.02	−0.01
Total	3.17	6.37	9.55	1.78	5.69	7.47	−2.08

References

[1] UNEP. Global mercury assessment. Geneva: United Nations Environment Programme Chemicals; 2002.
[2] UNEP. The global atmospheric mercury assessment: sources, emissions and transport. Geneva:United Nations Environment Programme Chemicals, Industry and Economics Division;2008.
[3] Pacyna EG, Pacyna JM. Global emission of mercury from anthropogenic sources in 1995. Water Air Soil Poll 2002;137:149–65.
[4] Chen YL, Wang R, Shen HZ, Li W, Chen H, Huang Y, et al. Global mercury emissions from combustion in light of International fuel trading. Environ Sci Technol 2014;48:1727–35.
[5] Pacyna EG, Pacyna JM, Steenhuisen F, Wilson S. Global anthropogenic mercury emission inventory for 2000. Atmos Environ 2006;40:4048–63.
[6] Pacyna EG, Pacyna JM, Sundseth K, Munthe J, Kindbom K, Wilson S, et al. Global emission of mercury to the atmosphere from anthropogenic sources in 2005 and projections to 2020. Atmos Environ 2010;44:2487–99.
[7] Pacyna JM, Sundseth K, Pacyna EG, Jozewicz W, Munthe J, Belhaj M, et al. An assessment of costs and benefits associated with mercury emission reductions from major anthropogenic sources. J Air Waste ManageAssoc 2010;60:302–15.
[8] Pirrone N, Cinnirella S, Feng X, Finkelman RB, Friedli HR, Leaner J, et al. Global mercury emissions to the atmosphere from anthropogenic and natural sources. Atmos. Chem. Phys. Discuss 2010;10:4719–52.
[9] Dabrowski JM, Ashton PJ, Murray K, Leaner JJ, Mason RP. Anthropogenic mercury emissions in South Africa: coal combustion in power plants. Atmos Environ 2008;42:6620–6.
[10] Glodek A, Pacyna JM. Mercury emission from coal-fired power plants in Poland. Atmos Environ 2009;43:5668–73.
[11] Burger Chakraborty L, Qureshi A, Vadenbo C, Hellweg S. Anthropogenic mercury flows in India and impacts of emission controls. Environ Sci Technol 2013;47:8105–13.
[12] Pai P, Niemi D, Powers. B, North A. American inventory of anthropogenic mercury emissions. Fuel Process Technol 2000;65–66:101–15.
[13] UNEP, Global Mercury Assessment 2013: sources, emissions, releases, and environmental transport. 2013, United Nations Environment Programme Environment for Development.
[14] Fu X, Feng X, Sommar J, Wang. S. A review of studies on atmospheric mercury in China. Sci Total Environ 2012;421–422:73–81..
[15] Wu Y, Wang S, Streets DG, Hao J, Chan M, Jiang. J. Trends in anthropogenic mercury emissions in China from 1995 to 2003. Environ Sci Technol 2006;40:5312–8.
[16] Fridley D. Embodied energy: an alternative approach to understanding urban energy use. Available from: 〈http://www.theoildrum.com/node/6842〉; 2010 [accessed 08.07.14].
[17] Dhakal S. Urban energy use and carbon emissions from cities in China and policy implications. Energy Policy 2009;37:4208–19.
[18] Fung PLK. New push for reform: signals from China's two parliamentary conferences. Available from: 〈https://www.kpmg.com/CN/en/IssuesAndInsights/ArticlesPublications/Documents/new-push-for-reform-China-Lianghui-201303-v1.pdf〉; 2013 [accessed 29.05.14].
[19] Chen C, Su M, Liu G, Yang Z. Evaluation of economic loss from energy-related environmental pollution: a case study of Beijing. Front Earth Sci 2013;7:320–30.
[20] Cao C, Jiang W, Wang B, Fang J, Lang J, Tian G, et al. Inhalable microorganisms in Beijing's PM2.5 and PM10 pollutants during a severe smog event. Environ Sci Technol 2014;48:1499–507.
[21] Murphy F, Devlin G, McDonnell K. Forest biomass supply chains in Ireland: a life cycle assessment of GHG emissions and primary energy balances. Appl Energy 2014;116:1–8.
[22] Menten F, Chèze B, Patouillard L, Bouvart F. A review of LCA greenhouse gas emissions results for advanced biofuels: the use of meta-regression analysis. Renew Sustain Energy Rev 2013;26:108–34.
[23] Castelo Branco DA, Moura MCP, Szklo A, Schaeffer R. Emissions reduction potential from CO_2 capture: a life-cycle assessment of a Brazilian coal-fired power plant. Energy Policy 2013;61:1221–35.
[24] Hong JL. Uncertainty propagation in life cycle assessment of biodiesel versus diesel: global warming and non-renewable energy. Bioresource Technol 2012;113:3–7.
[25] Huo H, Wang M, Bloyd C, Putsche V. Life-cycle assessment of energy use and greenhouse gas emissions of soybean-derived biodiesel and renewable fuels. Environ Sci Technol 2009;43:750–6.
[26] Shahabi MP, McHugh A, Anda M, Ho G. Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy. Renew Energy 2014;67:53–8.
[27] Hoekstra AY, Gerbens-Leenes W, van der Meer TH. Reply to Pfister and Hellweg: Water footprint accounting, impact assessment, and life-cycle assessment. Proc Natl Acad Sci 2009;106:E114.
[28] Jefferies D, Muñoz I, Hodges J, King VJ, Aldaya M, Ercin AE, et al. Water footprint and life cycle assessment as approaches to assess potential impacts of products on water consumption. Key learning points from pilot studies on tea and margarine. J Cleaner Prod 2012;33:155–66.
[29] Li JS, Chen GQ. Water footprint assessment for service sector: a case study of gaming industry in water scarce Macao. Ecol Indic 2014, 10.1016/j.ecolind.2014.01.034.
[30] Han M, Guo S, Chen H, Ji X, Li J. Local-scale systems input–output analysis of embodied water for the Beijing economy in 2007. Front Earth Sci 2014:1–13.
[31] Li JS, Alsaed A, Hayat T, Chen GQ. Energy and carbon emission review for Macao's gaming industry. Renew Sustain Energy Rev 2014;29:744–53.
[32] Li JS, Chen GQ, Wu XF, Hayat T, Alsaedi A, Ahmad B. Embodied energy assessment for Macao's external trade. Renew Sustain Energy Rev 2014;34:642–53.
[33] Leontief W. Environmental repercussions and the economic structure: an input–output approach. Rev Econ Stat 1970;52:262–71.
[34] Leontief WW. Quantitative input and output relations in the economic systems of the United States. Rev Econ Stat 1936;18:105–25.
[35] Chen Z-M, Chen GQ. Virtual water accounting for the globalized world economy: national water footprint and international virtual water trade. Ecol Indic 2013;28:142–9.
[36] Chen GQ, Chen ZM. Carbon emissions and resources use by Chinese economy 2007: a 135-sector inventory and input–output embodiment. Commun Nonlin Sci Numer Simul 2010;15:3647–732.
[37] Chen GQ, Zhang B. Greenhouse gas emissions in China 2007: inventory and input–output analysis. Energy Policy 2010;38:6180–93.
[38] Chen ZM, Chen GQ. Embodied carbon dioxide emission at supra-national scale: a coalition analysis for G7, BRIC, and the rest of the world. Energy Policy 2011;39:2899–909.
[39] Chen ZM, Chen GQ, Zhou JB, Jiang MM, Chen B. Ecological input–output modeling for embodied resources and emissions in Chinese economy 2005. Commun Nonlin Sci Numer Simul 2010;15:1942–65.
[40] Su B, Ang BW. Input–output analysis of CO_2 emissions embodied in trade: the effects of spatial aggregation. Ecol Econ 2010;70:10–8.
[41] Su B, Ang BW. Input–output analysis of CO2 emissions embodied in trade: a multi-region model for China. Appl Energy 2014;114:377–84.
[42] Feng K, Davis SJ, Sun L, Li X, Guan D, Liu W, et al. Outsourcing CO_2 within China. Proc Natl Acad Sci 2013;110:11654–9.
[43] Chen Z-M, Chen GQ. Demand-driven energy requirement of world economy 2007: a multi-region input–output network simulation. Commun Nonlin Sci Numer Simulat 2013;18:1757–74.
[44] Lenzen M. Understanding virtual water flows: a multiregion input–output case study of Victoria. Water Resour Res 2009;45:11.
[45] Lenzen M, Moran D, Bhaduri A, Kanemoto K, Bekchanov M, Geschke A, et al. International trade of scarce water. Ecol Econ 2013;94:78–85.
[46] Wang Y, Xiao HL, Lu MF. Analysis of water consumption using a regional input–output model: model development and application to Zhangye City, Northwestern China. J Arid Environ 2009;73:894–900.
[47] Ge J, Lei Y. Carbon emissions from the service sector: an input–output application to Beijing. China Clim Res 2014;60:13–24.
[48] Guo S, Liu JB, Shao L, Li JS, An YR. Energy-dominated local carbon emissions in Beijing 2007: inventory and input–output analysis. Sci World J 2012:10 (2012).
[49] Guo S, Shao L, Chen H, Li Z, Liu JB, Xu FX, et al. Inventory and input–output analysis of CO_2 emissions by fossil fuel consumption in Beijing 2007. Ecol Inform 2012;12:93–100.

[50] Zhou SY, Chen H, Li SC. Resources use and greenhouse gas emissions in urban economy: ecological input–output modeling for Beijing 2002. Commun Nonlin Sci Numer Simul 2010;15:3201–31.
[51] Liang S, Xu M, Liu Z, Suh S, Zhang. T. Socioeconomic drivers of mercury emissions in China from 1992 to 2007. Environ Sci Technol 2013;47:3234–40.
[52] Liang S, Zhang C, Wang Y, Xu M, Liu W. Virtual atmospheric mercury emission network in China. Environ Sci Technol 2014;48:2807–15.
[53] Guo S. Multi-scale systems accounting for energy use and carbon emissions in Beijing. college of engineering. Beijing: Peking University; 2013.
[54] Weber CL, Peters GP, Guan D, Hubacek. K. The contribution of Chinese exports to climate change. Energy Policy 2008;36:3572–7.
[55] Miller RE, Blair PD. Input–output analysis: foundations and extensions. Cambridge: Cambridge University Press; 2009.
[56] BSY. Beijing statistical yearbook. Beijing: China Statistics Press; 2011.
[57] Streets DG, Hao J, Wu Y, Jiang J, Chan M, Tian H, et al. Anthropogenic mercury emissions in China. Atmos Environ 2005;39:7789–806.
[58] Chen GQ, Guo S, Shao L, Li JS, Chen Z-M. Three-scale input–output modeling for urban economy: carbon emission by Beijing 2007. Commun Nonlin Sci Numer Simulat 2013;18:2493–506.
[59] Lee J-Y, Ju Y, Keener TC, Varma RS. Development of cost-effective noncarbon sorbents for HgO removal from coal-fired power plants. Environ Sci Technol 2006;40:2714–20.
[60] Sun C, Snape CE, Liu H. Development of low-cost functional adsorbents for control of Mercury (Hg) emissions from coal combustion. Energy Fuels 2013;27:3875–82.
[61] Xinhuanet. Beijing clean air action plan 2013–2017, 〈http://www.bj.xinhuanet.com/bjyw/2013-09/13/c_117351459.htm〉; 2013 [accessed 12.06.14].
[62] Harris PG, Chow ASY, Symons J. Greenhouse gas emissions from cities and regions: international implications revealed by Hong Kong. Energy Policy 2012;44:416–24.
[63] Li JS, Chen GQ. Energy and greenhouse gas emissions review for Macao. Renew Sustain Energy Rev 2013;22:23–32.
[64] Li JS, Chen GQ, Lai TM, Ahmad B, Chen ZM, Shao L, et al. Embodied greenhouse gas emission by Macao. Energy Policy 2013.
[65] Vause J, Gao LJ, Shi LY, Zhao JZ. Production and consumption accounting of CO_2 emissions for Xiamen, China. Energy Policy 2013;60:697–704.
[66] Zhang B, Chen GQ. Methane emissions by Chinese economy: inventory and embodiment analysis. Energy Policy 2010;38:4304–16.
[67] Zhang B, Li JS, Peng. BH. Multi-regional input–output analysis for China's regional CH_4 emissions. Front Earth Sci 2014;8:163–80.